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Spatial Variation Modeling of Geothermal Gradient and Heat Flow in Eastern Parts of Niger Delta Sedimentary Basin, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author EGO designed the study, performed the geostatistical analysis, wrote the protocol and the first draft of the manuscript. Author LIN managed the statistical analyses and literature searches of the study. Both authors read and approved the final manuscript.

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ABSTRACT

The aims of this research are to carry out statistical and geostatistical analysis of geothermal data and to determine the spatial variation of geothermal gradient and heat flow of parts of Niger delta sedimentary basin. Corrected Bottom hole temperatures from 18 deep oil wells were used for the computation of geothermal gradient and heat flows. The data were compiled from previous work. Both statistical and geostatistical analysis involving histogram, variogram, and ordinary kriging were applied to the data. The computed geothermal gradient values range from 16 – 33 ^{o}C/Km while the heat flow ranges from 23 to 70 mW/m^2. The statistical analysis of the geothermal gradient shows that the minimum, maximum, median, mean and standard deviation are; 15.57, 33.66, 21.27, 22.51 and 5.07 respectively. The most occurrence geothermal gradient interval in the histogram is 20-24°C/Km with a frequency of 9. For the heat flow values, the minimum, maximum, median, mean

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and standard deviation are: 21.99, 70.31, 44.19, 45.44, and 13.92. The most occurring heat flow interval is 51-61 mW/m^2 with a frequency of 5. The experimental variograms for the geothermal gradient and heat flow were modelled with spherical and Gaussian functions respectively. The heat flow variogram has nugget effect. The values of variances are assumed to be the values of the sill of the geothermal gradient and heat flow in the study area. The omnidirectional variogram provides a good interpretations for the spatial relationships for the two data sets. The ordinary kriging maps obtained from the variogram models for the geothermal gradients and heat flows provided a very good estimate for the un-sampled points. The geothermal gradient in the study area from the ordinary kriging ranges from 18 to 34.0°C/km, with an average value of 25.5°C/km. The geothermal gradient shows that the southeast region is associated with high values while northwest and central parts have low geothermal gradient respectively. The estimated heat flow from the ordinary kriging analysis ranges from 24 to 70 mW/m^2, with an average of 47.0 mW/m^2. The maximum heat flow occurs in the eastern and parts of the southwest regions. The lowest heat flow which trend in the northwest to southeast directions is found in the central region of the study area.

Keywords: Geothermal gradient; heat flow; statistics; variogram; kriging.

1. INTRODUCTION

The Niger Delta is one of the major sedimentary basins and the only discovered hydrocarbon bearing (for now) in Nigeria. It is ranked among the world major hydrocarbon reserve and it has been known for its large accumulation of oil and gas [1,2]. As a result of the abundance of oil and gas in the region, exploration and exploitation works started fifty years ago.

Many geoscientists [3,4,5] have computed the geothermal gradients and heat flow of the Niger Delta. According to [5], the heat flow of the northern Niger Delta sedimentary basin varies between 38.70 mWm^{-2} and 64.28 mWm^{-2} with an average of 51.49 mWm^{-2}. The geothermal gradients of the Niger Delta computed from well log by [6] ranges from 0.7 to 1.0°F/100 ft at the centre and 3°F/100ft in the northern part. [4], computed the geothermal gradient and heat flow in parts of the eastern Niger Delta from 71 wells and obtained geothermal gradient varying between 12 to 24°C/Km with an average of 17.6°C/Km in the coastal swamp, 14°C /Km to 26°C/Km with an average of 20.4°C/Km in the shallow offshore. They also observed heat flow values ranging from 29 to 55 mWm^{-2} with a mean of 42.5 mWm^{-2}. The geothermal gradients and heat flow values in the distal part of the Niger delta varies between 19-32°C/Km and 45-85 mWm^{-2} respectively according to [7]. Geothermal gradients values ranging from 25.47 to 31.16°C/Km with an average of 28.64°C/Km and heat flow values ranging from 38.93 to 89.59 mWm^{-2} were also obtained in parts of Delta state, Nigeria [8].

Knowledge of geothermal gradient and heat flow spatial variations is very important in basin modelling. Geostatistics make use of statistical tools for incorporating the spatial locations of observations in data processing, allowing for description and modelling of spatial patterns and estimation at unsampled locations [9,10]. The accurate prediction of subsurface geothermal data spatial distribution is very important in sedimentary basin modelling, crustal tectonics and hydrodynamics analysis, hydrocarbon and geothermal exploration. One technique that can be used to assess the spatial variation of geothermal data is geostatistics. This research focuses on the modelling of the spatial variation of geothermal gradient and heat flow in the study area. The objectives of the work are to determine the values of the heat flow and geothermal gradient in areas where there are no bottom hole temperature and to obtain a general view of the spatial variation of the geothermal data within the study area. The variogram model of the data was used for the Kriging estimation techniques.

Geostatistical methods analyse random events in terms of their spatial characteristics. They provide tools for explaining spatial continuity and the possibilities of regression models by incorporating spatial continuity in the model [11]. These methods are used to interpret and to predict the spatial distribution of the analyzed phenomena [11,12]. The geostatistic prediction involves the modeling of the experimental variogram and the estimation of heat flow and geothermal gradient at un-sampled locations. The modelled variogram was used for the analysis of the continuity, homogeneity and spatial structure of the data. The geostatistical estimation using ordinary kriging technique depends on the properties of the modelled variogram.

2. SUMMARY OF THE GEOLOGY OF THE STUDY AREA

The study area is located within the eastern parts of the Niger Delta sedimentary basin. It is located within longitude 5.5 to 8°E and latitude 3.5 to 6.5°N (Fig. 1). The geology of the Niger Delta and its hydrocarbon distribution pattern have been discussed by many researchers [13,14]. The Niger Delta is one of the most prolific areas in the world [15]. The Niger Delta is the youngest basin within the Benue Trough system. Its development began after the Eocene tectonic phase, and it has an average sedimentary thickness of about 12 km. The Rivers Niger and Benue are the major source of sediments to the basin.

Three lithostratigraphy are present in the Niger Delta. The lithostratigraphy are Benin, Agbada, and Akata Formations (Fig. 2). Hydrocarbon accumulation in the Niger Delta is confined to the Agbada Formation [16]. The uppermost section is the continental deltaic plain sands, which is known as the Benin Formation. The Benin Formation, is underlain by the Agbada Formation which is made up of alternation of sand and shale. The basal Akata Formation is made up of marine prodelta shale. Majority of the hydrocarbon accumulations in the Niger Delta occur in the Agbada Formation.

Growth structures are common in the Niger Delta, and they aid in the structural trap of the hydrocarbon [17,18,1].

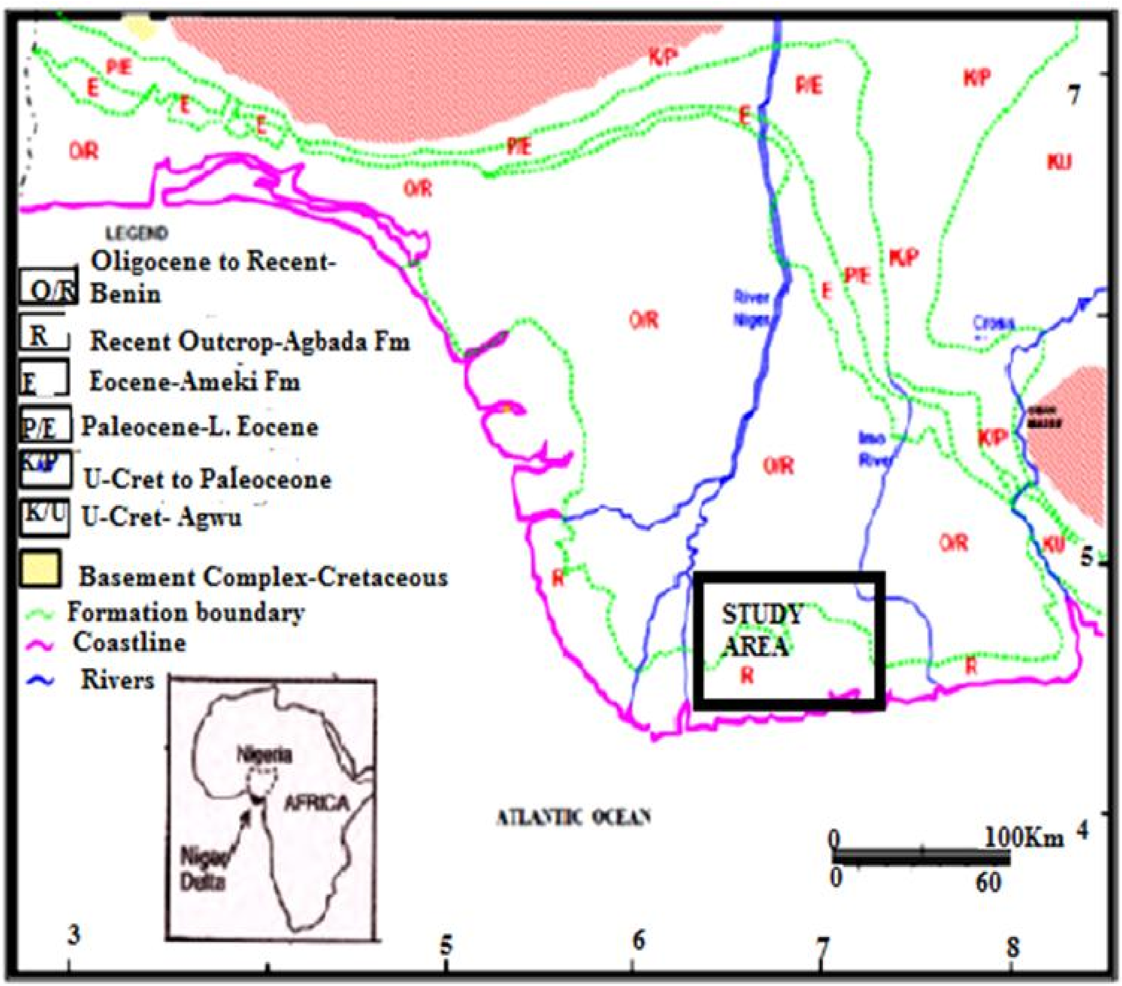

Fig. 1. Map of Niger Delta showing the study area (Modified from [19])

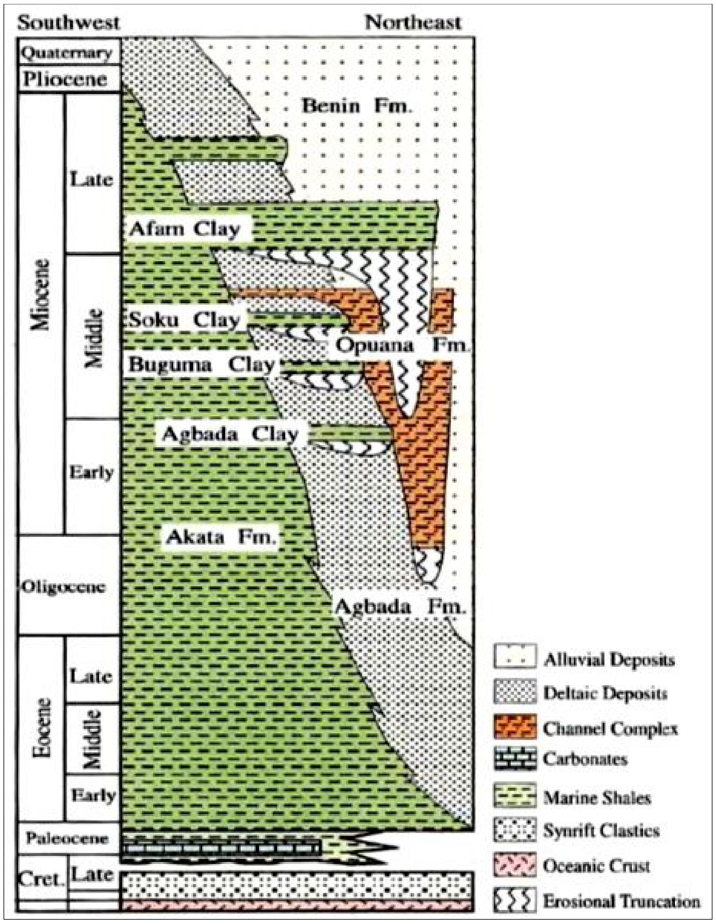

Fig. 2. Lithostratigraphy of the Niger Delta

3. METHODOLOGY

3.1 Dataset

The basic data used for this work are geothermal gradient and heat flow (Table 1) data obtained from previous study [20]. The geothermal gradient and heat flow were computed from corrected bottom hole temperatures and suite of well log obtained from 18 exploratory wells. The well logs data and bottom-hole temperature were obtained from Shell Petroleum Development Company. The average geothermal gradient and heat flow of each well was checked for quality and outliers. The procedure adopted includes; Exploratory data analysis, Variogram fitting and Kriging.

3.2 Exploratory Data Analysis

Exploratory Data Analysis is usually applied to data prior to geostatistical analysis. The purpose of the statistical analysis is to inspect the data properties whether there is a pattern in the dataset. The histogram of the data were plotted and after that the summary statistics was computed. The computed statistics include the minimum, maximum, mean, variance and standard deviation of the data. Finally, the histogram was plotted in the x-axis while the frequency (number of values per bin) in the Y-axis.

3.3 Variogram Analysis

A variogram might be thought of as "dissimilarity between point values as a function of distance", such that the dissimilarity is greater for points that are farther apart than points that are closer. The variogram is used for describing the structure of variations in a localised or regionalized variable [21,22]. It explains the variance in variable values due to differences in spatial locations of the analysed parameters. The semi-variogram is a function that provide half the variance of the continuity between all points separated by distance (h) and is inversely proportional to the distance of points in spatial analysis. The semi-variogram which is half the variogram is commonly used for modeling spatial distribution of data. The semi-variogram can be obtained with the equation 1 [22,11]:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i-1}^{N(h)}[Z(x_i+h)-Z(x_i)]^2 \quad (1)$$

Where:

$Z(x_i)$ = value of data
X_i = locations where measurement were performed
N(h) = number of pairs of points (x_i, x_i + h) separated by distance h

The experimental variogram is not enough for data analysis. Therefore, appropriate theoretical models are fitted on the generated variogram. Several theoretical models such as Gaussian, spherical, linear and exponential [21], were fitted on the experimental variogram and the best fit was selected.

Table 1. Geothermal gradient and heat flow data and their locations

Latitude (°)	Longitude (°)	Heat (mW/m²)	Grad (°C/Km)
4.85	6.9	29.12	15.57
4.75	7.45	35.17	20.09
4.63	6.2	60.54	20.09
5.5	6.4	44.19	17.9
4.2	6.5	56.85	33.66
4.26	6.49	45.85	29.58
3.7	6.495	39.43	20.07
4.15	6.75	52.14	29.45
4.1	7.1	42.33	21.66
4.5	7.5	21.99	17.04
4.23	7.55	68.1	22.9
4.63	6.35	53.3	21.49
6.25	6.9	41.84	20.6
5	6.75	23.06	27.43
4.73	7.9	70.31	27.43
4.23	5.99	35.19	20.67
5.14	7.5	54.64	21.27
5.32	6.45	37.78	15.88

3.4 Kriging Analysis

Kriging techniques provides the best linear unbiased estimators of the value of the analyzed regionalized variable. It is a geostatistical method that supports the identification of regularities in spatial distribution of data, and those regularities are used in spatial interpolation [11]. The kriging methods are used to estimate the unknown values of the analyzed phenomenon in a given location based on measurements (observations) performed at several known coordinates points. The kriging interpolation was calculated as a linear combination of regionalized random variables as shown in the equation 2:

$$Z^*(s_0)=\sum_{i-1}^{n} w_i Z(s_i) \quad (2)$$

where:

$Z^*(s_0)$ = estimated value,
$Z(s_i)$ = values observed in known locations,
Wi = weights or importance of the value Z(si).

It accounts for the distance between data and data estimation locations, their spatial configuration and spatial structure described by a theoretical semi-variogram.

4. RESULTS

The spatial distribution of geothermal gradient and heat flow computed from available bottom-hole temperatures are shown in Figs. 3 and 4. The locations of the data in Figs. 3 and 4 are the sites of the boreholes from which the geothermal gradient and heat flows were computed. The average of the parameters at each borehole are plotted in the map. A plot of the computed heat flow against the geothermal gradient is shown in Fig. 5. The scatter graph was fitted with a linear relationship given in equation 3 as;

$$Y = 1.1468X + 19.44 \quad (3)$$

Where

Y = Heat flow
X= Geothermal gradient

The regression coefficient obtained for the model is 0.1748. The value is very low due to the scattered nature of the data points. The histograms generated for the geothermal gradient and heat flow are shown in Figs. 6 and 7. The summary of the statistical analysis of the two datasets is shown in Table 2.

Figs. 8 and 9 show the computed experimental semi-variograms of the geothermal gradient and heat flow of the area. In both cases, the semi-variogram values increase with the separation distance, reflecting that the geothermal gradient and heat flow values close to each other are more alike, and thus their squared difference is smaller than those far apart. The modelled variograms were used for generating the ordinary kriging maps of the geothermal gradient and heat flow (Figs. 10 and 11) respectively. The geothermal gradient and heat flow variograms were modelled with spherical and Gaussian functions given in equations 4 and 5 as;

$$\gamma(h) = \left\{ c[1.5h - 0.5h^3 \right\} \quad \text{for } h < 1 \qquad (4)$$

or

$$\gamma(h) = c \quad \text{for } h \geq 1$$

and

$$\gamma(h) = C(1 - e^{(\frac{h^2}{a^2})}) \qquad (5)$$

Where

$\gamma(h)$ = Model variogram
C = Scale
h = Distance
a = Range

The Scale parameter (C) in the variogram equations define the sill of the variogram. The sill of the variogram model equals the nugget effect plus the sum of the Scale (C) parameters. In many situations, the variogram model sill is assumed to be equal to the variance of the observed data.

Surfer 13 software was used for generating the variogram, variogram model and the kriging maps. It was observed that the data has nugget effect. The properties of the model variograms of the geothermal gradient and heat flow are shown in Table 3. The value of the range (a) is unity in the model.

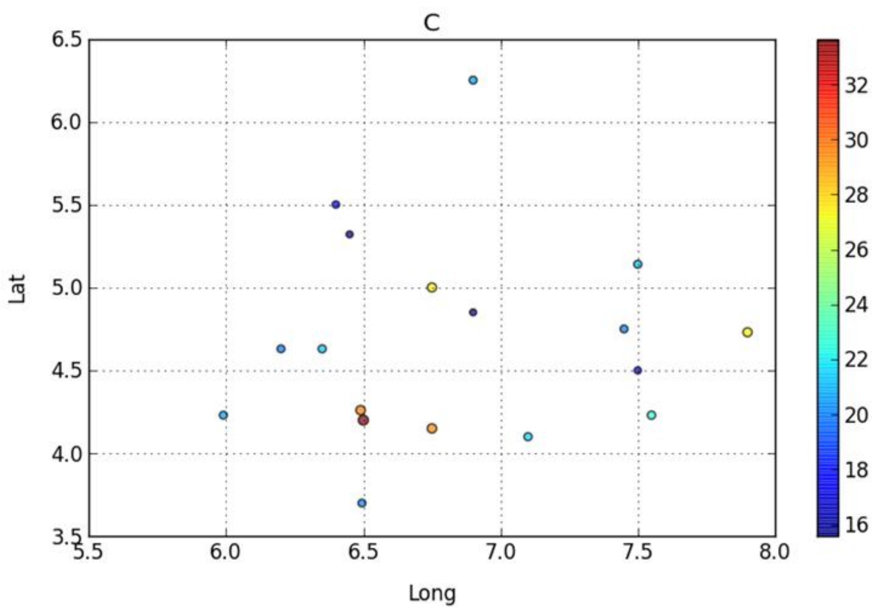

Fig. 3. Base map of the study area showing the geothermal gradient values (^{o}C/Km)

Table 2. Summary of computed geothermal gradient and heat flow statistics

Variable	Minimum	Maximum	Median	Mean	Standard deviation
Geothermal gradient (^{o}C/Km)	15.57	33.66	21.27	22.51	5.07
Heat flow (mW/m^2)	21.99	70.31	44.19	45.44	13.92

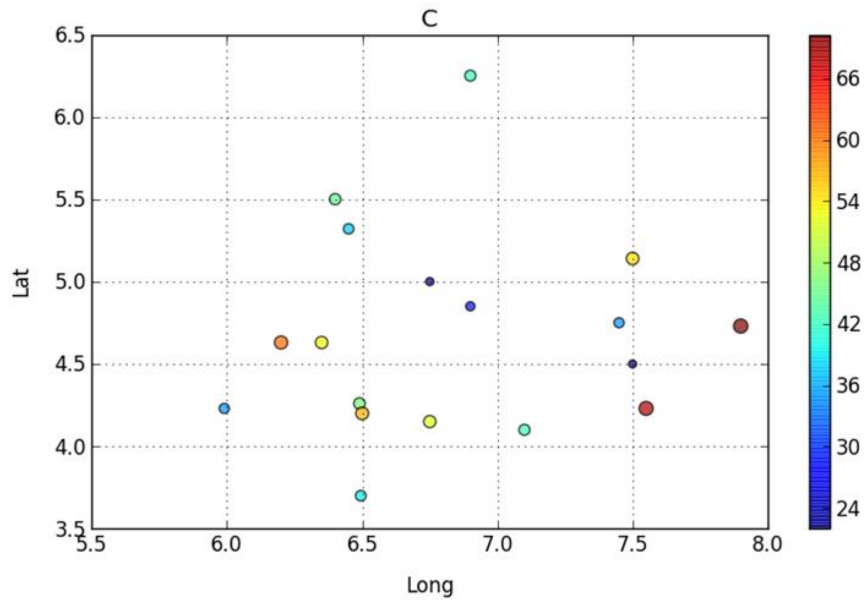

Fig. 4. Base map of the study area showing the heat flow values (mW/m^2)

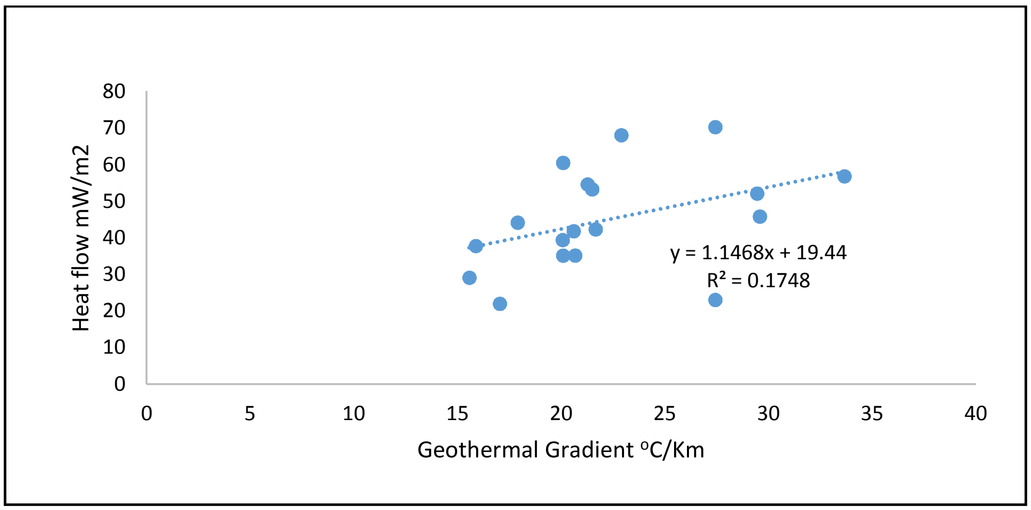

Fig. 5. A plot of heat flow against geothermal gradient

5. DISCUSSION

With respect to Figs. 3 and 4, it was observed that the data distribution in the study area is very scanty and are cluster. This is due to the limited numbers of deep oil boreholes drilled and their locations. Therefore, it is necessary to determine the geothermal gradient and heat flow at the un-sampled locations and their spatial variation. The graph of the heat flow versus geothermal gradient shows a very poor relationship. The regression coefficient is very low because the points are scattered.

The results of the statistical analysis of the geothermal gradient show that the minimum, maximum, median, mean and standard deviation are: 15.57, 33.66, 21.27, 22.51 and 5.07. The most occurrence geothermal gradient interval is 20-24 with a frequency of 9. For the heat flow values, the minimum, maximum, median, mean and standard deviation are: 21.99, 70.31, 44.19, 45.44, and 13.92. The results also show that the median and the mean are almost the same values. The most occurring heat flow interval is 51-61 with a frequency of 5.

With reference to Figs. 8 and 9, spherical and Gaussian models were fitted to the geothermal gradient and heat flow variograms respectively. The variogram model of the heat flow has nugget effect because it did not start from the origin. The error variance of the nugget effect of the geothermal gradient and heat flow are 0 and 20.1 respectively. The sill of the geothermal gradient and heat flow are 0.6583 and 252. The computed sills are assumed to be the values of the variance of the geothermal gradient and heat flow in the study area.

The estimated geothermal gradient in the study area from the ordinary kriging ranges from 18 to 34.0°C/km, with an average value of 25.5°C/km. The distribution of the geothermal gradient shows that the southeast region is associated with high values. The northwest and central parts have low geothermal gradient respectively. The

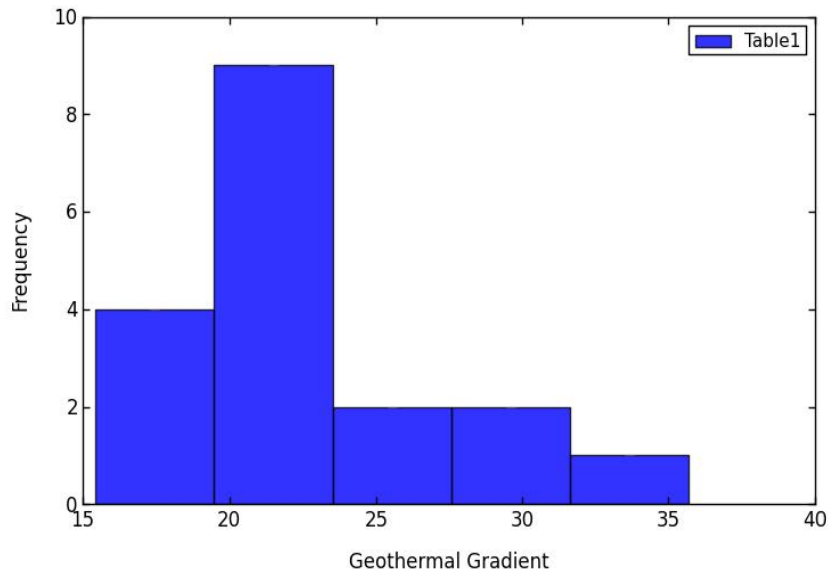

Fig. 6. Histogram of the geothermal gradient (^{o}C/Km)

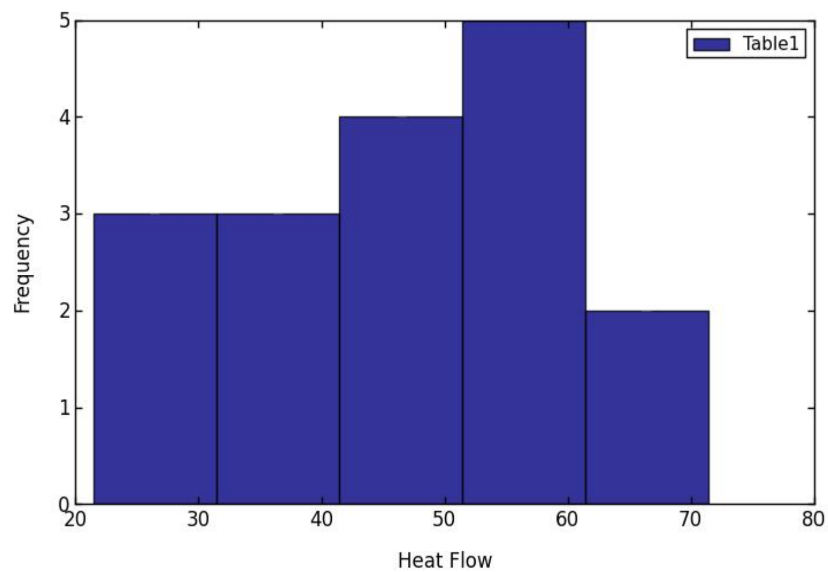

Fig. 7. Histogram of the heat flow (mW/m^2)

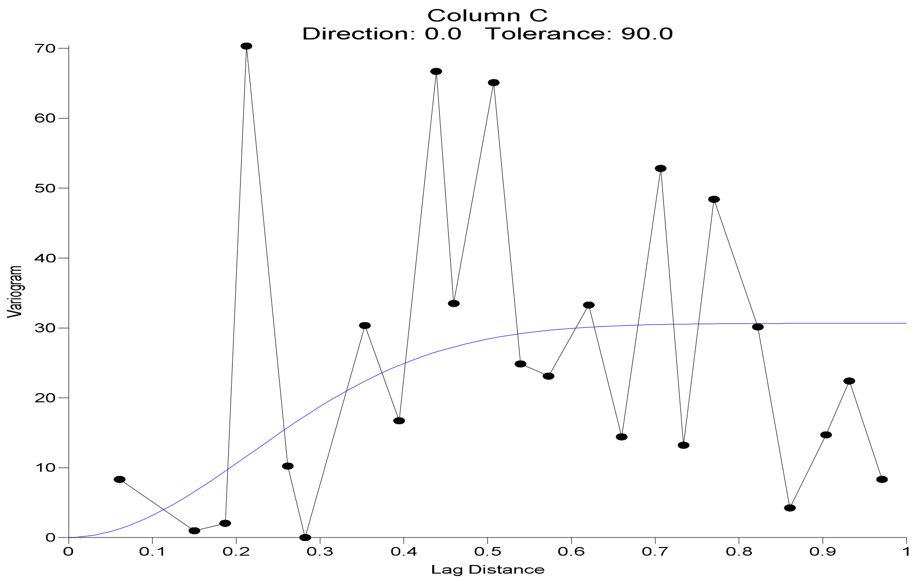

Fig. 8. Computed variogram and variogram model for geothermal gradient

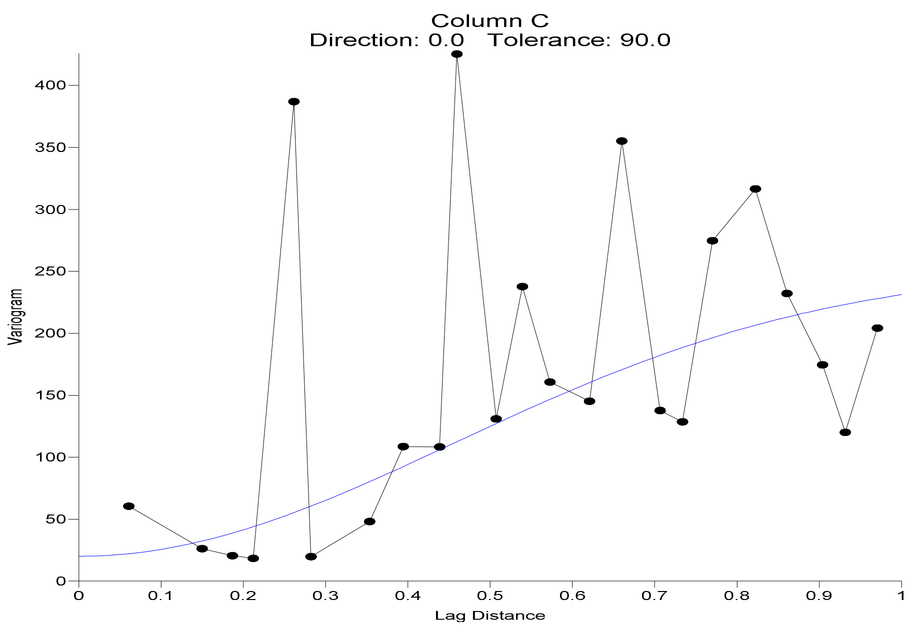

Fig. 9. Computed variogram and variogram model for geothermal gradient

estimated heat flow from the ordinary kriging analysis in the study area ranges from 24 to 70 mW/m^2, with an average of 47.0 mW/m^2. The highest heat flow occurs in the eastern and parts of the southwest regions. The lowest heat flow which trend in the northwest to southeast directions is found in the central region of the study area. The low heat flow may be attributed to high sedimentary thickness [23].

The possible factors influencing the thermal regime in includes depth to basement, sedimentary thickness and hydrothermal convection [4,5]. The study area is tectonically not active and minute heat is supplied from the mantle into the basin. The estimated geothermal gradient and heat flow are in agreement with the values obtained in other tectonically stable and inactive regions of the world [24,25].

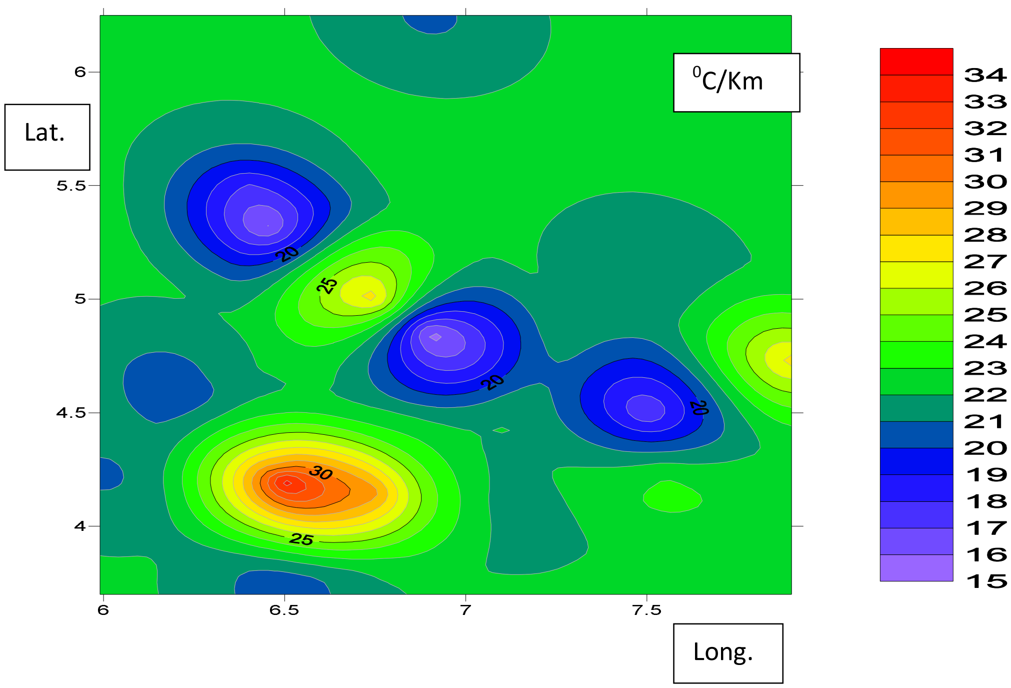

Fig. 10. Geothermal gradient map calculated using ordinary kriging algorithm

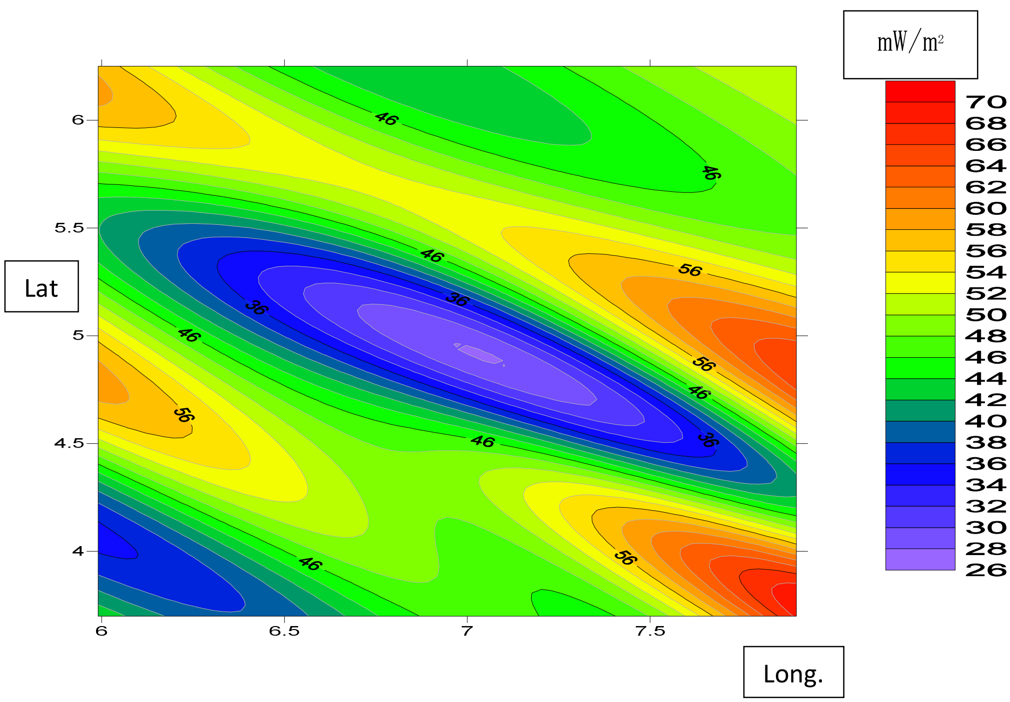

Fig. 11. Heat flow map calculated using ordinary Kriging algorithm

Other possible factors affecting the thermal regime of the area are hydrothermal convection of fluids through local and regional faults and fractures, and hydrocarbon fields. Seismic data obtained from part of the study area [26,27,18,19] showed the presence of growth, synthetic and antithetic faults in the subsurface (Fig. 12). The faults trend mainly in the northeast-southwest direction. These faults are partly responsible for direction of migration of subsurface fluid. The thickness of the Niger Delta decreases from about 12km in the west to about 3 Km in the east (Fig. 13). This shows that the thickness decreases eastward and it also correspond to an increasing heat flow [28]. The central region of the heat flow map with low heat flow may be as a result of high sedimentary thickness and depth to basement while the eastern region with high heat flow may be attributed to low sedimentary thickness and depth to basement.

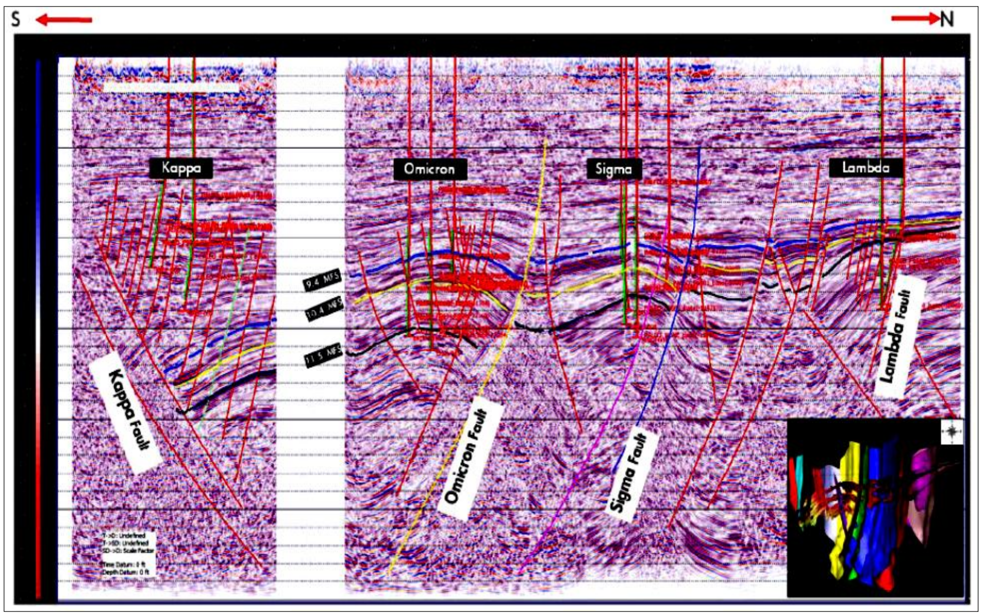

Fig. 12. Seismic data from part of the study area with complex fault structures

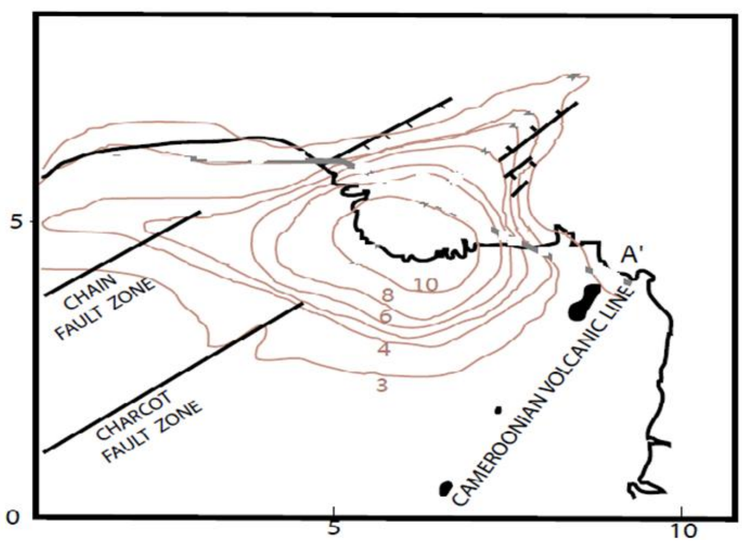

Fig. 13. Isopach map of the Niger Delta sedimentary basin (Modified from [29])

Table 3. Properties of the modeled variogram

Geothermal gradient (°C/Km)		Heat flow (mW/m^2)	
Component Type:	Nugget effect	Component type:	Nugget effect
Error Variance:	0	Error variance:	20.1
Micro Variance:	0	Micro variance: 0	
Component Type:	Spherical	Component Type:	Gaussian
Anisotropy Angle:	60	Anisotropy Angle:	140
Anisotropy Length:	0.4767	Anisotropy Length:	2.05
Anisotropy Ratio:	1.2	Anisotropy Ratio:	4.8
Variogram Scale:	0.6583	Variogram Scale:	232

5. CONCLUSION

The statistical and geostatistical analysis techniques have been used for performing spatial distribution and estimation of the geothermal gradient and heat flow at un-sampled points. Spatial dependency of the parameters was moderate. Gaussian model with nugget effects was fitted for the heat flow variogram while the geothermal gradient variogram was fitted with spherical model. The ordinary kriging maps obtained from the variogram models show good estimate of the missing data at the unsampled points. The geostatistics modelling show spatial distribution models and spatial dependence levels of the geothermal data. The assessment of the spatial variability of the geothermal gradient and heat flow is very important in basin modelling.

COMPETING INTERESTS

The authors hereby declared that there are no competing interests.

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